

# Bistatic Synthetic Aperture Radar with Application to Moving Target Detection

A. P. Whitewood, B. R. Müller, H. D. Griffiths and C. J. Baker

Bistatic radar involves the use of a physically separated transmitter and receiver. This paper describes a bistatic radar system which uses the combination of a spaceborne synthetic aperture radar transmitter on board the European Space Agency's Envisat satellite, and a low-cost, stationary, ground-based receiver. The advantages of this variant of the bistatic configuration involve the passive and therefore undetectable nature of the receiver, in addition to standard bistatic considerations such as forward scatter.

Experimental results obtained using the receiver, and an analysis into the utility of the system for moving target detection in the presence of clutter, based on a simulation in Matlab of the electronic Displaced Phase Centre Antenna technique are both presented. It is found that the DPCA method considered has a possible signal-to-clutter-and-noise ratio after cancellation and processing of approximately 10dB, although this is with the assumption of adequate received pulses and so integration gain, to offset the signal-to-noise ratio degradation caused by the canceller.

A discussion of future experimental work, including the possible use of two such receivers for an investigation into interferometry concludes.

**Index Terms**— bistatic radar, moving target detection, synthetic aperture radar (SAR), Displaced Phase Centre Antenna (DPCA)

## I. INTRODUCTION

Bistatic Radar has experienced a resurgence of interest over the last five years, and as a result is currently an active area of research. The physical separation of transmitter and receiver confers certain advantages to the system, and in particular, a passive receiver may use radiation from a non-cooperative transmitter, without revealing the receiver location. This of course has military applications, with the potential use of an

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enemy's radar by a receiving system that is immune to countermeasures. The so-called 'illuminators of opportunity' investigated previously have included ground-based television transmitters [1] and [2], GSM base stations [3], and satellites [4]-[6], transmitting a variety of waveforms, not all of which, e.g. communication signals, are optimum for surveillance. It is the satellite-based illuminator that has been identified by the US Department of Defense as an important component of future AMTI and GMTI systems [7] and [8], and which forms the basis of this particular investigation.

In [9] the concept of a Bistatic Radar Imaging System using the European Space Agency's Envisat satellite, and in particular, the Advanced Synthetic Aperture Radar (ASAR) instrument as the transmitter and a static ground-based receiver was introduced. The main aims of this paper are to present some experimental results and analysis for this system, and to propose a unique implementation of the electronic form of DPCA. Section II describes the receiver, in terms of the hardware, a waveform capture, and a SAR processor written in Matlab. Section III is a feasibility study on the utility of the system for moving target detection in clutter, based on computer simulations of the electronic Displaced Phase Centre Antenna (DPCA) technique in Matlab. Section IV outlines the experiments to be undertaken over the next three to six months including geometry considerations and a possible investigation into interferometry.

## II. THE RECEIVER SYSTEM

A block diagram of the receiver is shown in Fig. 1 [9]:

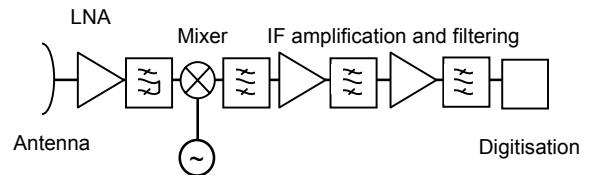


Fig. 1. Block diagram of the receiver system

A 1.2m diameter parabolic antenna is used, mounted on the roof of a University-owned building in central London. The direct signal from the satellite is received via a sidelobe, and reflected signals via the mainlobe. The waveform transmitted by the Envisat ASAR instrument is a 16MHz chirp centred on a frequency of 5.331GHz i.e. C Band. This is down converted in the receiver to an intermediate frequency of 124MHz,

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before being digitised using a Compuscope 8500 digitiser card in preparation for processing. The dynamic range of the direct and echo signals received in this way is such that the resolution of the Compuscope board, at 8 bits, is adequate. The detection performance of the system was considered in [9], and indicated that a single pulse signal-to-noise ratio of +10dB should be expected, for a target-to-receiver range of 50km and a target radar cross-section of +20dBm<sup>2</sup>.

The tests performed on the receiver have included characterisation, in addition to a capture of the signal produced at the output, given a locally generated input signal, as shown in Fig. 2.

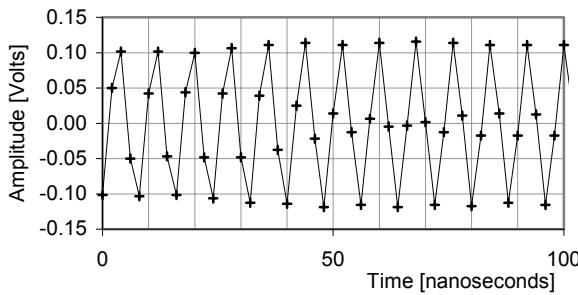


Fig. 2. Capture of the signal output by the receiver, given a continuous wave signal applied to the input

A signal amplitude of  $-80\text{dBm}$  is applied to the input of the receiver, producing the output shown. This has been sampled by the Compuscope board at a rate of 500MS/s. The root-mean-squared output amplitude is approximately 72mV or  $-9.8\text{dBm}$ , commensurate with an overall gain of 70.2dB. A SAR Chirp Scaling processor, based on information given in [10] has been programmed in Matlab in preparation for the experiments due to commence early this year. This will produce a single-look complex image that can be compared to the equivalent monostatic image produced by the European Space Agency (ESA).

### III. ELECTRONIC DPCA FOR BISTATIC RADAR

DPCA is a relatively well known technique used to compensate for platform motion that otherwise spreads the clutter spectrum thus concealing moving targets. Here we consider applying the technique to this form of bistatic radar. As we can only exert control over the receiver component of the system we have examined the performance of an implementation of the electronic form of DPCA at reception (despite the fact that the receiver is static). Results of the theoretical optimum improvement evaluations for the application of the deduced processor on the considered bistatic configuration are presented.

The basic geometry and the meaning of the relevant geometrical variables is illustrated in Fig. 3. A plane approximation of the real geometry is used, with the x-y-plane representing the earth's surface. The x-axis is parallel to the

satellite velocity vector, and the centre of the receiver antenna beam lies within the y-z-plane (the z axis is not shown, but is defined to be perpendicular to the x-y plane). The centre of the satellite antenna beam is always parallel to the y-z-plane and is indicated by a dotted line. The angle  $\vartheta$  is the satellite look angle in the azimuth direction for a single ground scatterer,  $\phi$  is the corresponding receiver azimuth look angle. There are two different situations illustrated, at time  $t=t_0$  the satellite is at the position  $x_s < 0$  and at a time  $t>t_0$  the satellite has moved to the position  $x_s = 0$ .

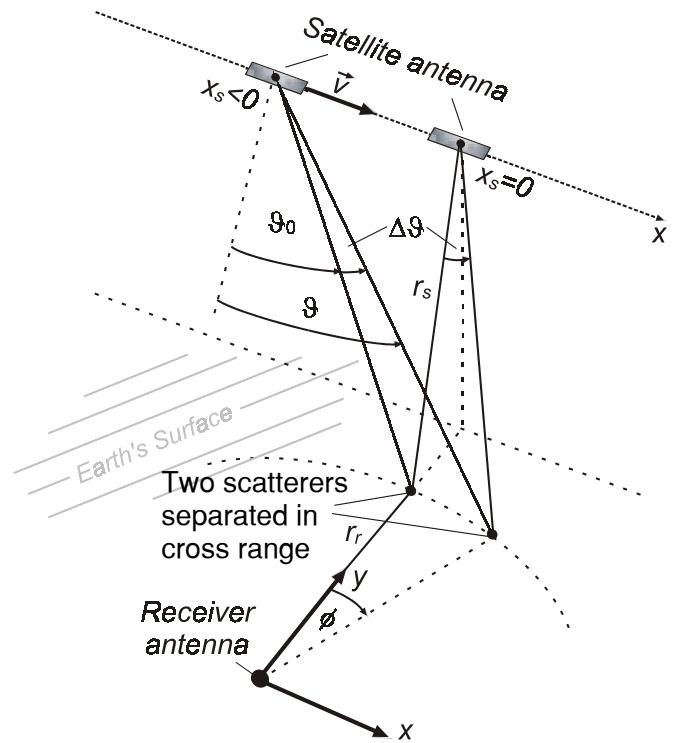


Fig. 3. Geometry and nomenclature used

The structure of the bistatic DPCA processor, shown in Fig. 4, is very similar to that of a corresponding monostatic canceller described in Skolnik [11], with the main difference being the double-bounded "Transmitter Position Compensation" that will be explained later in this Section. The input signals  $\Sigma(t)$  and  $\Delta(t)$  represent the sum and difference channels of a monopulse antenna and are connected by the relationship

$$\Delta(t) = j\Sigma(t) \cdot \tan\left(\frac{\pi W}{\lambda} \sin \phi\right) \quad (1)$$

where  $W$  is the distance between the two phase centres of the antenna,  $\phi$  is the receiver look angle and  $\lambda$  represents the wavelength of the radar signal.

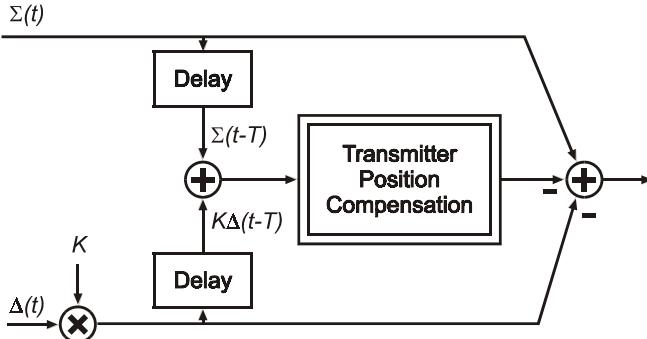


Fig. 4. Block diagram of a bistatic DPCA processor

The principle may be understood by examining the sum-channel phasor diagram in Fig. 5, showing the effects of the DPCA algorithm on the received echoes  $\Sigma(t_0)$  and  $\Sigma(t_0+T)$ , corresponding to a single ground scatterer.

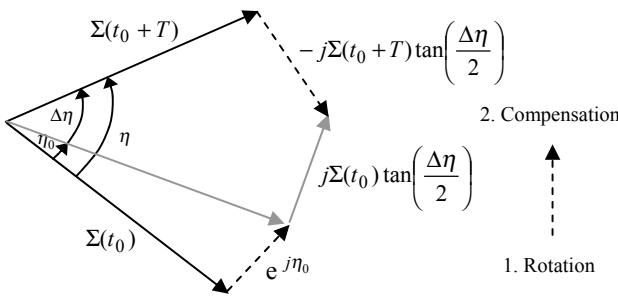


Fig. 5. Phasor diagram for a single clutter scatterer

The phase advance  $\eta$  due to satellite motion can be calculated as:

$$\eta = \frac{2\pi v T}{\lambda} \sin(\vartheta) \approx \underbrace{\frac{2\pi v T}{\lambda} \sin(\vartheta_0)}_{\eta_0} + \underbrace{\frac{2\pi v T}{\lambda} \sin(\Delta\vartheta)}_{\Delta\eta} \quad (2)$$

where  $v$  is the satellite velocity,  $T$  is the pulse repetition interval, and  $\vartheta$  is the look angle of the satellite in the azimuth direction. For small values and all clutter scatterers of interest,  $\vartheta$  can be split into the angle fractions  $\vartheta_0$  and  $\Delta\vartheta$  as shown in Fig. 3. This expansion is also valid for small  $\vartheta_0$  values. The angle  $\vartheta_0$  is approximately constant for all clutter points received within the same range cell and can be estimated when the position of the transmitter  $x_s$  is known. Thus, the rotation by the angle  $\eta_0$ , accomplished during the "Transmitter Position Compensation" stage, can be implemented as a complex multiplication by a factor  $e^{j\eta_0}$ .

As indicated in Fig. 5, optimum compensation could now be achieved if the signal

$$\sigma(t) = j\Sigma(t) \cdot \tan \frac{\Delta\eta}{2} = j\Sigma(t) \cdot \tan \left( \frac{\pi v T}{\lambda} \sin \Delta\vartheta \right) \quad (3)$$

was available. However, assuming small angles,  $\sin \Delta\vartheta$  can be approximated by

$$\sin \Delta\vartheta \approx \frac{r_r}{r_s} \sin \phi \quad (4)$$

with  $r_s$  and  $r_r$  denoting the distance of the clutter point from the satellite (for  $x_s=0$ ) and from the receiver respectively.

Using equation (4) in (3) gives:

$$\sigma(t) \approx j\Sigma(t) \cdot \tan \left( \frac{\pi v T}{\lambda} \frac{r_r}{r_s} \sin \phi \right) \quad (5)$$

The optimum distance  $W$  between the two phase centres of the antenna is given by:

$$W = W_{opt} = \frac{v T r_r}{r_s} \quad (6)$$

In practical applications,  $W$  is determined by system constraints such as the required antenna beamwidth, and so equation (6) may not be satisfied. The optimum case can be approximated by introducing a weighting  $K$ , that compensates for the difference between the optimum and actual values of  $W$ .

Thus,  $\sigma(t)$  can be approximated by:

$$\sigma(t) \approx K \cdot \Delta(t) \quad (7)$$

$K$  is a constant that must be determined individually for each range in order to minimise the clutter residue.

A similar constant is also found in monostatic DPCA systems, but in contrast to the bistatic case it may remain fixed for all ranges - [11].

The DPCA canceller as described above has been simulated for discrete geometries of the bistatic configuration considered in this paper. For this purpose a phased array model with a beamwidth of  $3^\circ$  and a sidelobe level relative to mainlobe of 13.25dB was used for the receiver antenna. Furthermore, the following simplifications for the clutter characteristics have been assumed:

- The illuminated area is homogeneous with constant bistatic radar cross section per unit area  $\sigma_c^0$ .
- The spectral spread caused by internal motion is Gaussian-shaped with mean value  $\mu=0$  and standard deviation  $\sigma_i=20\text{Hz}$ .
- Reflections from different receiving look angles  $\phi$  are uncorrelated
- No obstacles disturb the wave propagation after the first reflection on the ground.

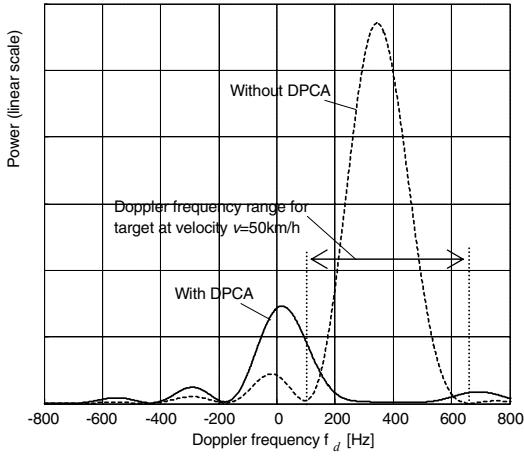


Fig. 6. Effect of the DPCA processor on the clutter spectrum

A representative result for the effects on the clutter band is shown in Fig. 6, corresponding to a low-flying target at a range of 30km from the receiver antenna and a satellite misalignment of  $x_s = -2.4\text{km}$ , causing the asymmetry of the spectrum. It can be observed that on the one hand the cancellation of unwanted reflections received by the antenna mainlobe is quite satisfactory, despite the adverse transmitter location, but on the other hand the clutter power due to the sidelobes increases significantly. However, comparison with the depicted Doppler frequency range of a target with a velocity of 50km/h, indicates that substantial improvement in signal-to-clutter-ratio (SCR) may be achievable for slowly moving objects if additional processing of coherent pulses is accomplished afterwards.

Before viewing results for overall output SCR, a significant disadvantage of all systems using cancellation methods must be examined. Not only the clutter power but also the return signal of targets (with or without a small self-caused Doppler-shift) decreases dramatically, whereas the receiver noise is amplified. The effect on the signal-to-noise ratio (SNR) for a target with Doppler-frequency  $f_d$  is approximately given by equation (8) - [12].

$$SNR_{out} = SNR_{in} \cdot \frac{4\sin[(f_d - f_c^{\max})\pi T]^2}{2 + 2K^2} \quad (8)$$

where  $SNR_{in}$  denotes the SNR at the input,  $SNR_{out}$  is the SNR at the output of the DPCA processor,  $K$  is the same constant as in (7) and  $f_c^{\max}$  is the Doppler frequency for which optimum cancellation occurs.

Taking both aspects - clutter and noise, into account, numerical computations for the overall performance have shown promising results as presented below.

Assuming a bistatic radar cross section  $\sigma_t = 20\text{dBm}^2$  for a target at range 30km and  $\sigma_c^0 = -10\text{dB}$  for the ground clutter an input signal-to-clutter-ratio of  $SCR_{in} = -16.4\text{dB}$  can be estimated (a one-pulse input SNR of 10dB and the provision of 200 ideal coherent pulses is assumed). Hence, the total

signal-to-clutter-and-noise ratio (SCNR) after DPCA cancellation and optimum processing can be calculated as illustrated in Fig. 7:

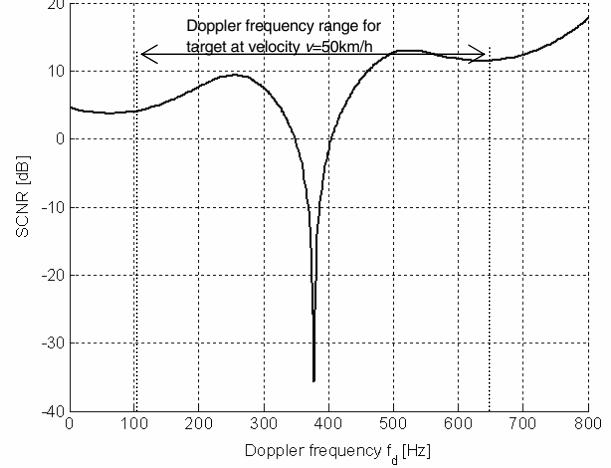


Fig. 7. Overall signal-to-noise and signal-to-clutter ratio for a low-flying target at range 30km from the receiver

Fig. 7 corresponds to a target in the centre of the receiver antenna beam, and with a satellite misalignment of  $x_s = -2.4\text{km}$ .

Again the possible values for the target Doppler shift regarding a velocity of 50km/h are also displayed. Comparison with Fig. 6 confirms that an acceptable SCNR of approximately 10dB is achievable within regions of the original spectrum which are heavily disturbed by clutter returns.

#### IV. PROPOSED EXPERIMENTAL INVESTIGATION

Cherniakov [13] has considered the feasibility of such Space-Surface Bistatic SAR Systems and in particular, notes that the geometry of the situation, in addition to the satellite velocity vector have an effect on the achievable space resolution. As the path of the Envisat satellite is well-known, the experiments have been planned to take advantage of an optimum transmitter-target-receiver geometry, as shown in Fig. 8.

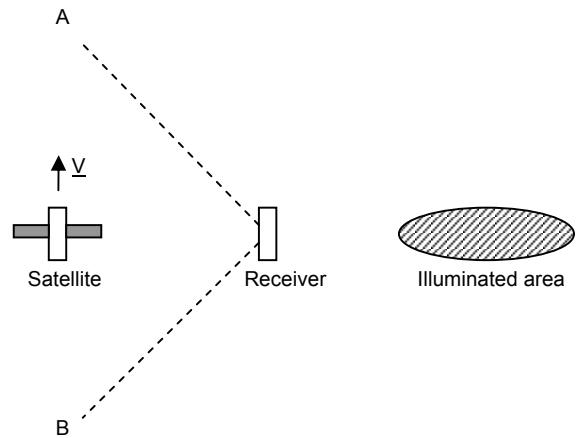


Fig. 8. Top view of optimum geometry

The satellite is shown with velocity vector  $\underline{V}$ , and lying within an area defined by A-Receiver-B. This is a specific case of the analysis outlined in [13], for which the range and cross-range resolutions are similar to their monostatic counterparts, albeit with a cross-range resolution of twice the monostatic value. The resolution achievable by the ASAR instrument for a single-look image is stated in [14] as 9m x 6m (range x azimuth), and so an ideal azimuth resolution of 12m would be expected. Degradation of the resolution in one or both directions results for different geometries and satellite velocity vector directions, with the situation being alleviated through the use of multiple receivers.

Another possible area of investigation is that of interferometry, through the use of two separate receivers. The monostatic situation is illustrated in Fig. 9.

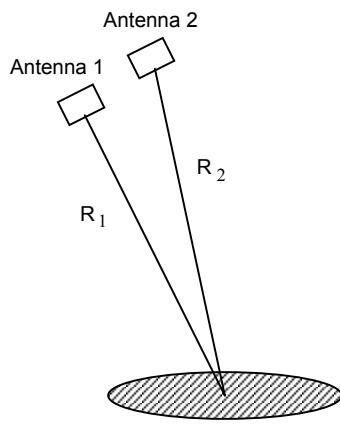


Fig. 9. Geometry for monostatic SAR Interferometry

The two antennas are mounted on a moving platform, airborne or spaceborne, with slant ranges to some point on the ground  $R_1$  and  $R_2$ . In standard mode, one antenna transmits and both receive, while in 'ping-pong' mode, the antennas transmit and receive alternately - [15].

Compare this to the bistatic arrangement shown in Fig. 10, with two stationary receivers and a moving, spaceborne transmitter:

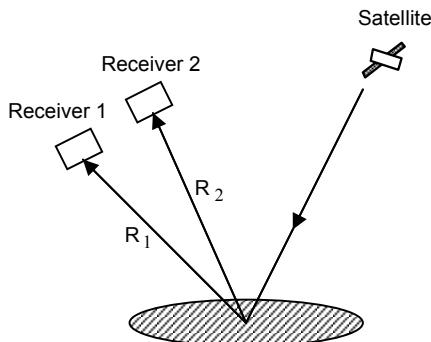


Fig. 10. Possible bistatic SAR Interferometry experiment

The slant ranges  $R_1$  and  $R_2$  are again from each receiver to a point on the ground. For conventional across-track interferometry, we form an interferogram by multiplying one image,  $S_1$  by the complex conjugate of the other,  $S_2^*$ , the procedure being identical in the Bistatic case. The phase difference between the images generated by antenna 1 and antenna 2 is:

Monostatic:

$$\phi = \arg(S_1 S_2^*) = \frac{2\pi p}{\lambda} (R_1 - R_2) \quad (9)$$

$p=1$  for standard mode,  $p=2$  for 'ping-pong' mode.

Bistatic:

$$\phi = \frac{2\pi}{\lambda} (R_1 - R_2) \quad (10)$$

The bistatic phase difference is half the corresponding monostatic value for 'ping-pong' mode, and identical to the value obtained for standard mode, for a given path length difference. In this way it may be that this form of bistatic interferometry reduces the degree of processing difficulty compared to a 'ping-pong' mode system. In addition, it is expected that system sensitivity equations, derived from the geometry, and obtainable from [15], should be the same as for a monostatic standard mode system.

As for the monostatic case, a 'phase unwrapping' procedure must also be carried out in order to remove the ambiguity in the phase measurements.

## V. CONCLUSIONS

This paper has presented experimental results obtained using a low-cost stationary receiver that forms part of a bistatic synthetic aperture radar system, with the Envisat ASAR instrument as the transmitter.

The well-established monostatic electronic DPCA technique has been applied to the bistatic geometry, despite the receiver being stationary. Theoretical analysis in Matlab has verified that adequate suppression of clutter received by the antenna mainlobe is achievable providing a solid base for further Doppler processing. A limiting factor is the decrease in SNR caused by the DPCA canceller for slowly moving targets - this emphasises the need for a large number of coherent pulses to establish an adequate integration gain.

Finally, we have proposed further experimental investigations, and shown that the interferometric principle may be applied to this form of bistatic radar, and is equivalent to a monostatic standard mode system.

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